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VLBI CLOCK SYNCHRONIZATION TESTS PERFORMED VIA THE ATS-1 & ATS-3 SATELLITES

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DECEMBER 1971

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(NASA-TM-X-65818) VLBI CLOCK
SYNCHRONIZATION TESTS PERFORMED VIA THE
ATS-1 AND ATS-3 SATELLITES J. Ramasastry,
et al (NASA) Dec. 1971 16 p CSCL 22B

N72-18834

Unclas
17747

G3/30

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SUMMARY

Clock synchronization experiments were carried out May 10 to June 10, 1971, by the NASA/Goddard Space Flight Center and the Smithsonian Astrophysical Observatory via the ATS-1 and 3 geostationary satellites at the NASA tracking stations Rosman and Mojave, during a VLBI (Very Long Baseline Interferometer) experiment in order to determine the clock-offset between the two stations. 10μ sec pulses at C-band with very sharp risetime were exchanged by the two stations through the dual transponders of the satellites. At each station, a time-interval counter was started by the transmitted pulse and stopped by the received pulse. The probable error of the difference in the mean values of the clock-offset is 10 nanoseconds.

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VLBI CLOCK SYNCHRONIZATION TESTS VIA THE ATS-1 AND ATS-3 SATELLITES

I. INTRODUCTION

As part of a VLBI experiment performed jointly by NASA/Goddard Space Flight Center and Smithsonian Astrophysical Observatory during May 10 - June 10, 1971, the two clocks at the ends of the baseline were compared during each data run. Therefore, each day when data was taken, the clocks were compared to determine their relative offset. The ground stations were the ATS ground stations at Mojave, California, and Rosman, North Carolina. Microwave transmissions at C-band through dual transponders of the geostationary satellites ATS-1 and ATS-3 were used to make the comparison. The clocks were driven by rubidium frequency standards that were transported to the two ground stations to obtain the local oscillator frequencies for the SHF transmitters and receivers.

A measure of the time difference between the two clocks was obtained from recordings made of time-interval unit (TIU) measurements. The measurements by the TIUs were made every second for one minute at the same Greenwich mean time (GMT). The precision of the TIUs was ten nanoseconds and the accuracy of the measurements was determined from the root mean square (rms) of difference of the readings of the TIUs. It was found that ATS-3 measurements had a smaller spread than ATS-1 data, and it is felt that this is due to a better signal noise ratio (SNR) obtained with ATS-3. The higher SNR is obtained from higher spacecraft (s/c) EIRP and link geometry. The locations of the ground stations and satellites were as follows:

<u>STATION</u>	<u>LATITUDE</u>	<u>LONGITUDE</u>
Mojave	35°17' N	116°53' W
Rosman	35°11' N	82°52' W
<u>SATELLITE</u>	<u>INCLINATION</u>	<u>LONGITUDE</u>
ATS-1	3.349°	149.152° W
ATS-3	1.738°	78.850° W

II. TEST CONFIGURATION

A simplified block-diagram of the test configuration at the two ground stations is shown in Figure 1. The time synchronization tests were performed via ATS-1 and ATS-3, principally the latter because of higher signal levels. Both satellites are electrically similar, the major difference is that the ATS-3 antenna is mechanically despun on both transmit and receive, whereas the ATS-1 transmit antenna is an electronically despun phased array (the receive antenna is a collinear array). The uplink on ATS-1 is approximately 7 db weaker than on ATS-3 because of the collinear array.

The ATS spacecrafts are provided with two independent C-band transponders, which may be operated simultaneously contingent upon power load on spacecraft by other instruments. Transponder #1 has a receive frequency of 6212 MHz and a transmit frequency of 4119 MHz and transponder #2 receives on 6301 MHz and transmits on 4178 MHz. The EIRP of ATS-1 transponders with two Traveling Wave Tubes (TWT) is 52.2 dbm and ATS-3 transponder #1 with two TWTs is 54.6 dbm and transponder #2 is 56.5 dbm. During the time synchronization tests, Mojave transmitted to transponder #1 and received transponder #2, with Rosman operating on the alternate transponders. As a result of the different EIRPs, the signal level at Mojave is 4.3 db less when using ATS-1, and the signal level at Rosman is 2.4 db less.

The satellites may be operated in either a single sideband/phase modulation (SSB/PM) mode or a frequency translation (FT) mode. The FT mode was used for the VLBI and the time synchronization experiments. In the FT mode, the s/c acts as a simple frequency translator with no signal processing. The uplink signal is down converted to a 70 MHz intermediate frequency (IF), which is hard limited, and then is amplified and up-converted to the downlink frequency. The bandwidth of each transponder is 30 MHz. The hard limiting is almost down to the noise; therefore, in a 30 MHz bandwidth, the s/c transmits almost as much noise with no signal as when saturated with an uplink signal, the latter case actually being only 2 db greater.

To achieve the largest SNR possible and to bypass the suppression effects of hard limiting, each station transmitted to separate transponders. Mojave transmitted to transponder #1 and Rosman transmitted to transponder #2. Each station transmitted a carrier that was deviated 10 MHz for each 10 microsecond clock pulse. Since clock pulses were generated at a rate of 1 pps (pulse per second), the output signal from the ground stations consisted of a CW (continuous wave) carrier that was shifted 10 MHz each second for ten microseconds. By referring to Figure 1, it can be seen that the clock pulse from the delay generator is distributed by the uplink amplifiers to the

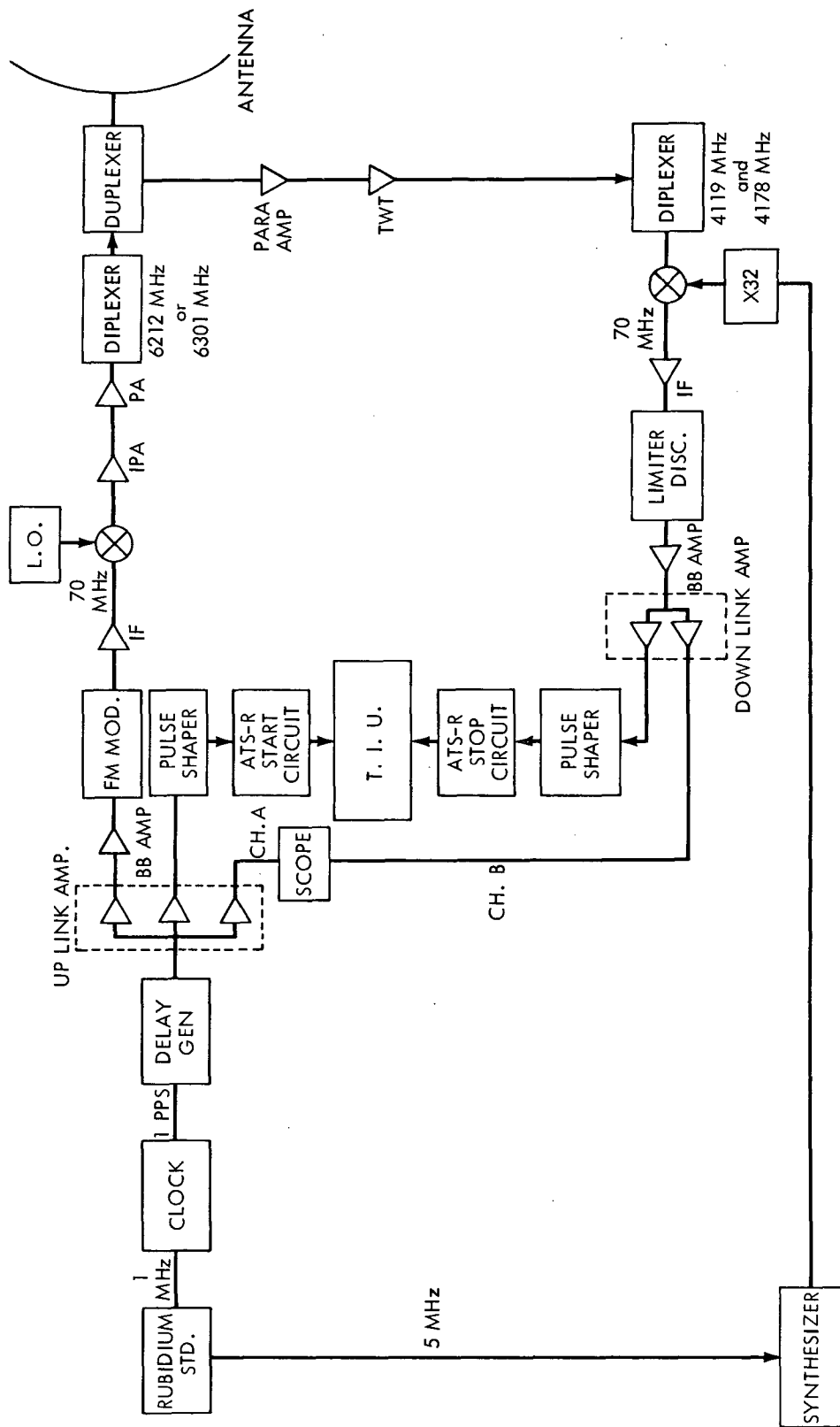


Figure 1. Ground Station Configuration for Time Sync. Expt.

FM modulator, pulse shaper and an oscilloscope. The scope is used to check pulse shape before making a time measurement. The pulse shaper circuit is used to start the time-interval unit counter (TIU).

The received signal at each station is converted to 70 MHz IF and limited and detected with an FM discriminator. The detected signal is then passed through the baseband amplifier and downlink distribution amplifiers to the scope and the stop circuit of the TIU. The elapsed time between the start and stop pulse is measured by the TIU with a precision of ten nanoseconds. The TIU output was recorded on punched paper tape at a rate of one sample per second. Each sample set was either 30 or 60 seconds long so that 30 or 60 samples were taken for each set of data.

III. GENERAL PRINCIPLES

Pulses were generated at a rate of 1 pps by the clocks at the two stations. The delay generator provides pulses of ten microseconds duration that deviate the carrier frequency by 10 MHz. A parallel output of the delay generator is used to start the TIU.

The signal received from the alternate ground station is detected by the limiter discriminator. The output of the discriminator is fed to the pulse shaper and driver. The leading edge of the pulse from the driver stops the TIU. In effect, the TIU measures the elapsed time between the start pulse of the local clock and the stop pulse from the remote clock. The elapsed time is measured and recorded at both ground stations. The time difference between the two clocks is determined from these recordings.

IV. NOTATION AND EQUATIONS

A. Notation (refer to Figure 2)

a_1, a_2 = time delays from uplink distribution amplifier input to TIU for stations 1 and 2 respectively.

b_1, b_2 = time delays from uplink distribution amplifier, through transmitter, to the antenna feed for stations 1 and 2 respectively.

c_1, c_2 = time delays from antenna feed, through the receiver and baseband amplifier for stations 1 and 2 respectively.

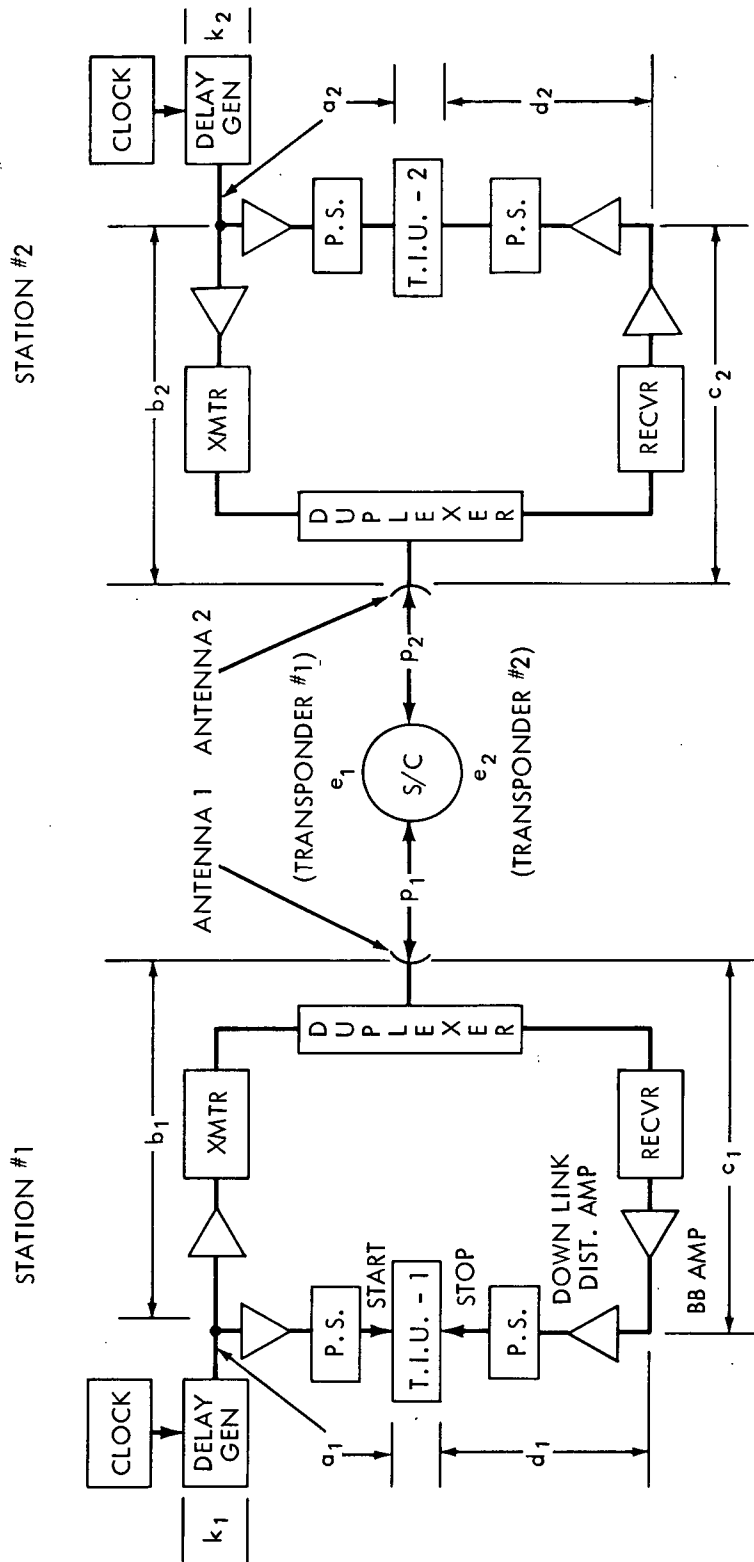


Figure 2. System Delays

d_1, d_2 = time delays through the down link distribution amplifier, pulse shaping network and into the TIU for stations 1 and 2 respectively.

e_1, e_2 = time delays through spacecraft transponders 1 and 2 respectively.

p_1, p_2 = propagation time delays from station antenna to the spacecraft for stations 1 and 2 respectively.

k_1, k_2 = time delay set in delay generators for stations 1 and 2 respectively.

t_1, t_2 = epochs of the clocks at stations 1 and 2 respectively.

E = offset between the clocks at stations 1 and 2 (positive if station 2 is ahead of station 1).

T_{r1}, T_{r2} = times of received pulses at stations 1 and 2 respectively.

T_1, T_2 = epochs of start of TIU for stations 1 and 2 respectively.

As can be seen in Figure 3, the time interval between transmitted and received pulses as measured at station 1 is given by:

$$(TIU)_1 = T_{r1} - T_1 \quad (1)$$

$$T_{r1} = t_2 + k_2 + b_2 + p_2 + e_2 + p_1 + c_1 + d_1 \quad (2)$$

$$T_1 = t_1 + k_1 + a_1 \quad (3)$$

$$T_2 = t_2 + k_2 + a_2 \quad (4)$$

$$(TIU)_1 = t_2 + k_2 + b_2 + p_2 + e_2 + p_1 + c_1 + d_1 - t_1 - k_1 - a_1 \quad (5)$$

The offset between the two epochs is:

$$E = t_2 - t_1 \quad (6)$$

Equation 5 can be rewritten to be:

$$(TIU)_1 = E + k_2 + b_2 + p_2 + e_2 + p_1 + c_1 + d_1 - k_1 - a_1 \quad (7)$$

Following the same procedure as above, the time interval at station 2 becomes:

$$(TIU)_2 = -E + k_1 + b_1 + p_1 + e_1 + p_2 + c_2 + d_2 - k_2 - a_2 \quad (8)$$

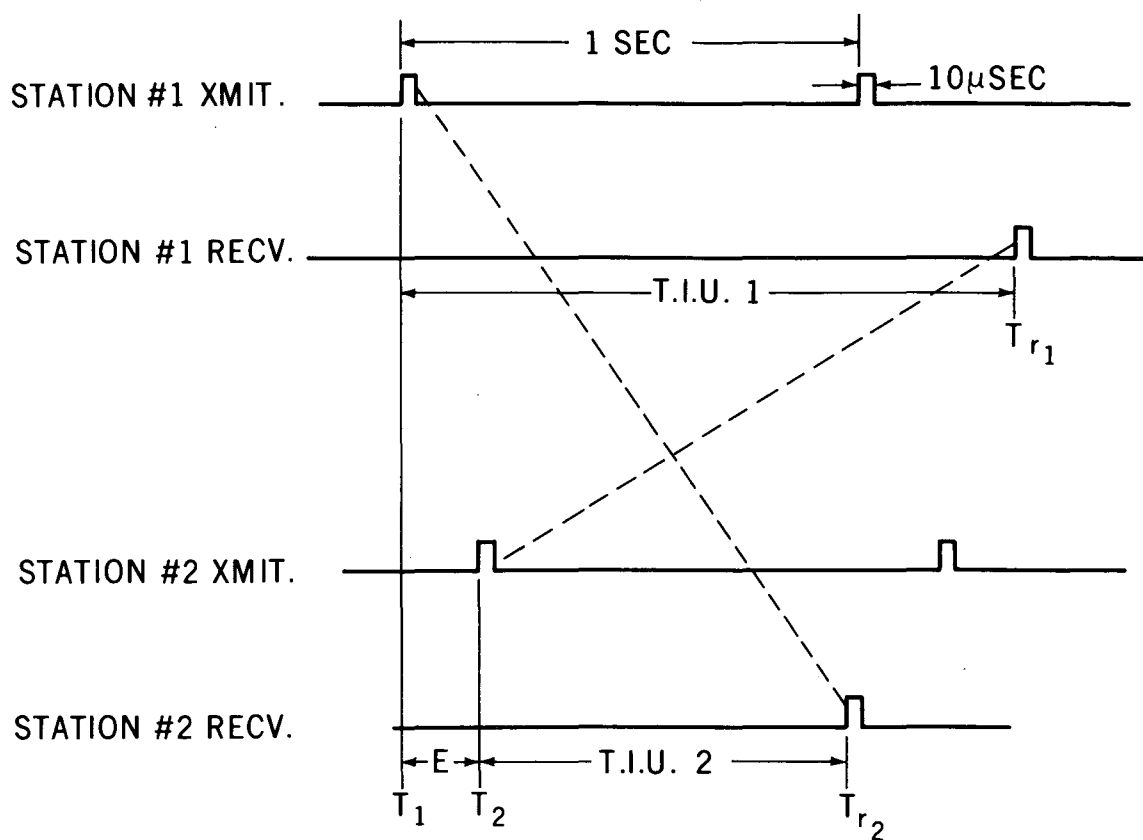


Figure 3. Timing Diagram

The difference between equations (7) and (8) is:

$$\Delta T = 2E + (k_2 - k_1) + (b_2 - b_1) + (p_2 - p_1) + (e_2 - e_1) + (p_1 - p_2) + (c_1 - c_2) + (d_1 - d_2) + (k_2 - k_1) + (a_2 - a_1) \quad (9)$$

The TIUs are monitored near simultaneously (within a second) therefore, the propagation-path delays in equation (9) cancel out and we get:

$$\Delta T = 2E + 2(k_2 - k_1) + (b_2 - b_1) + (e_2 - e_1) + (c_1 - c_2) + (d_1 - d_2) + (a_2 - a_1) \quad (10)$$

The time offset between the two clocks is obtained from equation (10) as:

$$E = -(k_2 - k_1) + 1/2 [\Delta T - (b_2 - b_1) - (e_2 - e_1) - (c_1 - c_2) - (d_1 - d_2) - (a_2 - a_1)] \quad (11)$$

It is evident from equation (11) that if the corresponding delays at the two stations were equal, then the time error would be 1/2 of the difference of the TIU counter readings. This is not the case however and the respective delays must be included in the solution for the clock error. The measured delay differences are as follows:

$$\begin{aligned} -(k_2 - k_1) &= +0.755 \text{ microseconds} \\ -(b_2 - b_1) &= -0.29 \text{ microseconds} \\ -(e_2 - e_1) &= 0 \text{ microseconds} \\ -(c_1 - c_2) &= -0.04 \text{ microseconds} \\ -(d_1 - a_1) &= -0.26 \text{ microseconds} \\ +(d_2 - a_2) &= -9.63 \text{ microseconds} \end{aligned}$$

It should be mentioned in this context that each of the above instrumental delays was measured separately and summed and compared with the total instrumental delay of the loop which included all of these individual delay sources. The difference between the two was zero measured to a precision of ± 10 nanoseconds.

$$E = \frac{\Delta T}{2} - 4.36 \text{ microseconds} \quad (12)$$

In this report Mojave has been designated as station #1 and Rosman as station #2. Since ΔT has been defined as the Mojave TIU reading minus Rosman's TIU reading, a positive value E indicates that the Mojave clock is ahead of the Rosman clock. Since there is a bias of 4.36 microseconds due to external delays, the TIU difference must be 8.71, $[(TIU)_2 - (TIU)_1 = -8.71 \mu \text{ sec}]$,

microseconds before the clocks are synchronized. Expressed another way, when the TIU at Mojave is 8.71 microseconds ahead of the TIU at Rosman, the two stations are synchronized.

V. DATA ANALYSIS

During each time synchronization test, the time-interval counter readings were taken simultaneously for a period of 60 seconds at one sample per second at both Mojave (station #1) and Rosman (station #2). The counter reading differences were computed for each sample and averaged over the 60 second period. The standard deviation was also computed for the 60 samples used in each analysis. On some occasions, more than 2 minutes of data (120 samples) were taken. The results are presented in Table 1. ΔT is the difference in the reading of the Mojave and Rosman time-interval counters at any one time. E is the actual time difference between the Mojave and Rosman clocks after accounting for all instruments and cable delays. $\sigma(E)$ is the standard deviation in nanoseconds. As one follows the change in E with time, one will notice some abrupt changes in E of the order of a few microseconds. These changes are due to (1) external delay or advance initiated in the Rosman clock to keep the difference between the two counter readings close to a prescribed value ($5 \mu \text{ sec}$) and (2) one or two jumps in the clock due to power failures at the tracking stations. The advantage of the time synchronization test is that one is able to accurately estimate these jumps without appriori information on these jumps. The Mojave VLBI clock had been compared to the Goldstone JPL Echo site clock and the Rosman VLBI clock had been slaved to USNO Washington, D.C. Therefore, independent crude checks on clock jumps were available, but none of them were as accurate as the time-synchronization readings.

Figure (4) presents clock asynchronization versus time. The data points indicated are actual measurements made during the experiment (after correcting for the instrumental delays as explained in the text). Also shown in the figure are the two occasions when the Rosman clock was reset during the experiment. On a third occasion (day 158), Rosman clock had jumped by $2.8 \mu \text{ sec}$ because of a power failure. When the experiment was conducted on that day, the jump was accurately detected. The clock-offset values indicated in the figure are used to correct the time delays measured while cross-correlating the interferometer data from Rosman and Mojave.

Figure (5) presents the uncompensated clock offset versus time. In this figure, all the delays introduced during the experiment have been removed. Thus one can use the information presented here to compute the long-term drift of the time standards which amounts to less than $0.5 \mu \text{ sec/day}$ during the 26 day period.

Table 1

Time Synchronization Data

Date	Time (GMT)	Satellite	$\frac{\Delta T}{2}$ (μsec)	E (μsec)	σ (E) nsec	Comment
May 12, 1971	22:46:00	ATS-3	+ 0.550	-3.810	5	Mojave clock still erratic
May 13	21:25:00	ATS-3	+ 0.183	-4.177	17	
May 18	15:27:00	ATS-1	+ 1.522	-2.838	30	
May 18	18:05:00	ATS-1	+ 1.564	-2.796	25	
May 18	23:29:00	ATS-1	+ 1.558	-2.802	20	
May 19	20:25:00	ATS-3	+ 1.632	-2.728	23	
May 20	20:38:00	ATS-3	+ 3.657	-0.703	14	
May 20	22:34:00	ATS-3	+ 3.643	-0.717	16	
May 20	22:51:00	ATS-3	-2.379	-6.739	14	
May 24	20:34:00	ATS-3	+ 0.559	-3.801	9	
May 24	22:35:00	ATS-3	+ 0.571	-3.789	7	Rosman clock set ahead 6.0 μsec
May 25	20:34:00	ATS-3	+ 0.822	-3.538	15	Rosman clock set ahead 5.0 μsec
May 26	22:14:00	ATS-3	+ 1.003	-3.357	10	
May 26	23:35:00	ATS-3	+ 1.008	-3.352	4	
June 1	21:35:00	ATS-1	+ 5.425	+ 1.065	43	
June 1	21:41:00	ATS-1	+ 0.421	-3.939	43	
June 2	22:28:00	ATS-3	+ 0.149	-4.211	7	
June 3	21:54:00	ATS-3	-0.351	-4.711	8	
June 3	23:24:00	ATS-3	-0.322	-4.682	24	
June 7	21:44:00	ATS-3	+ 6.450	+ 2.090	11	
June 7	23:04:00	ATS-3	+ 6.493	+ 2.133	9	
June 8	11:59:00	ATS-1	+ 6.275	+ 1.915	43	Rosman clock jumped 2.8 μsec
June 8	18:00:00	ATS-1	+ 6.182	+ 1.822	33	
June 8	21:00:00	ATS-3	+ 6.117	+ 1.757	4	
June 8	22:53:00	ATS-3	+ 6.103	+ 1.743	4	
June 8	23:13:00	ATS-3	+ 6.101	+ 1.741	4	

$$\Delta T = \{ \text{TIU (Mojave)} - \text{TIU (Rosman)} \} \text{ microseconds}$$

$$E = \left\{ \frac{\Delta T}{2} - 4.360 \right\} \text{ microseconds}$$

$\sigma(E)$ = the standard deviation in nanoseconds

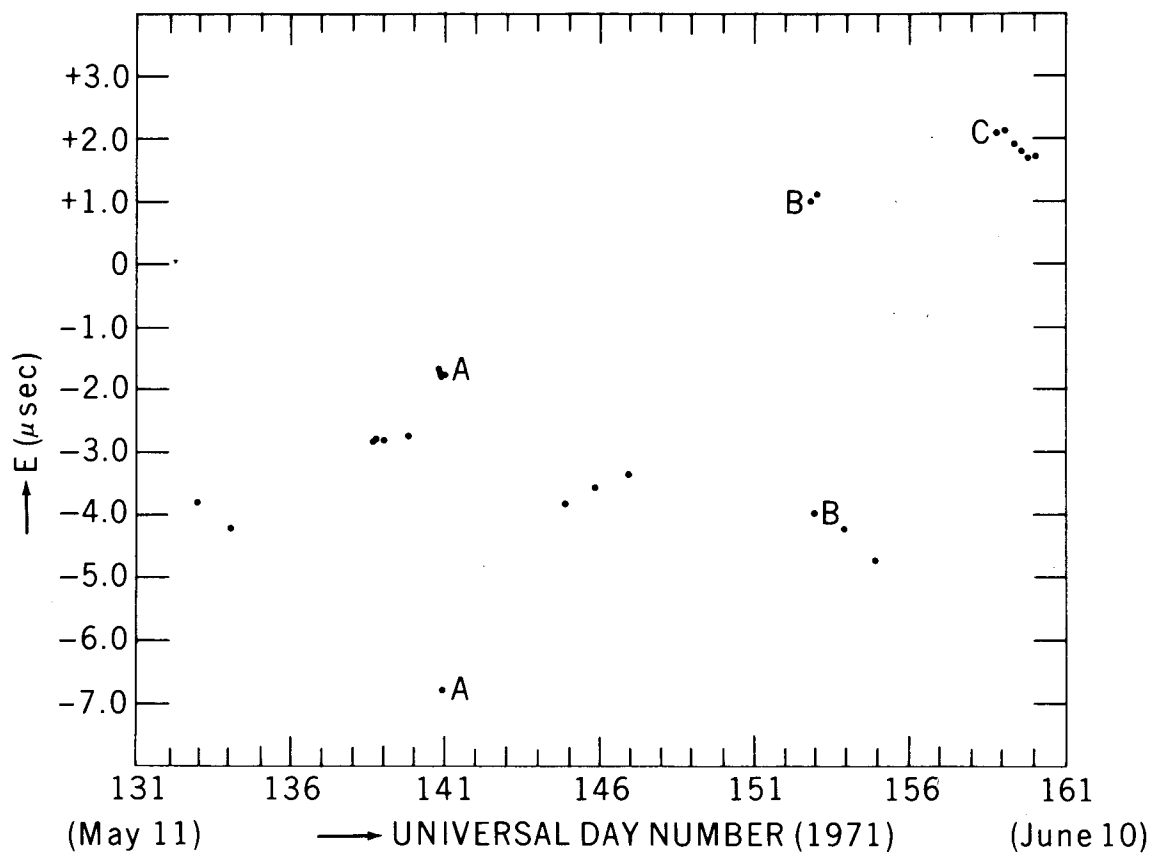


Figure 4. Clock Asynchronization versus Time

A \rightarrow Rosman clock set ahead 6 μsec

B \rightarrow Rosman clock set ahead 5 μsec

C \rightarrow Rosman clock jumped 2.8 μsec during power failure.

$$E = \left[\frac{\Delta T}{2} - 4.36 \right] \mu\text{sec}$$

$$\Delta T = \text{TIU (Mojave)} - \text{TIU (Rosman)}$$

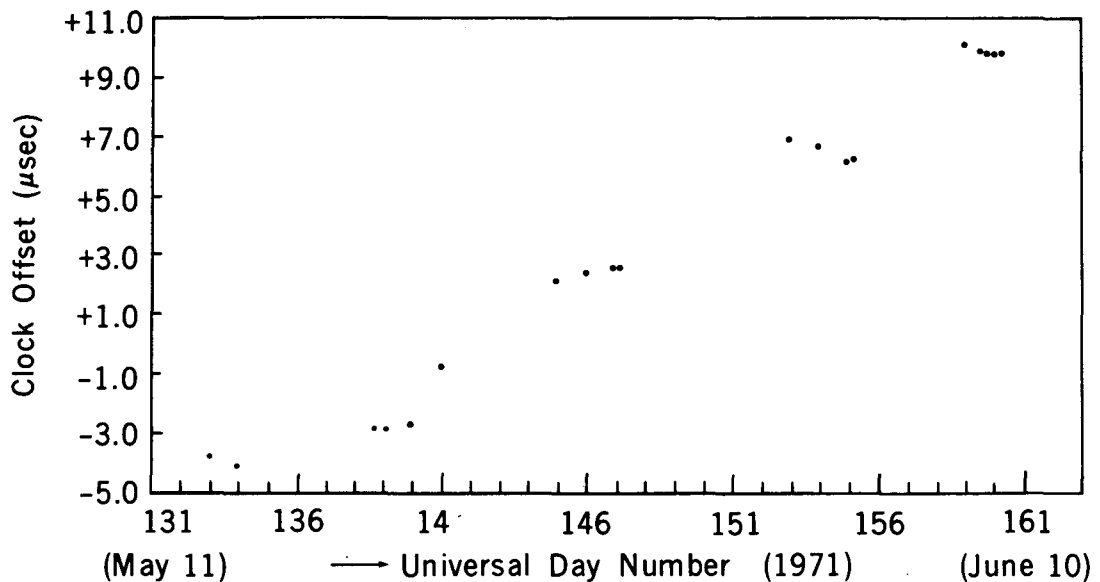


Figure 5. Uncompensated Clock-Offset versus Time (Positive Sign Indicates that Mojave Clock is Ahead of Rosman Clock.) Drift Rate $< 0.5 \mu\text{sec/day}$

Acknowledgement:

The cooperation and interest of the NASA ATS Project personnel and the engineers and technicians of Mojave and Rosman tracking stations is acknowledged. The JPL/Goldstone Echo site personnel provided portable clock trips to the Mojave site.

Our thanks are also due to Dr. F.O. Vonbun, Dr. D.E. Smith and Mr. Metzger of NASA/Goddard Space Flight Center, for their interest in the VLBI project.

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